A Capstone Design Project to Meet the Needs of the Changing Power Systems Industry and Satisfy New Accreditation Standards

Paul D. Hines, *Student Member, IEEE*, and Richard D. Christie, *Member, IEEE*

***Abstract*--Currently two motivators are effecting change in power systems education. First, the industry's transition to a more competitive environment is requiring changes in the content and pedagogy of power systems education. Second, engineering education as a whole is seeking to modify its curricula to reflect a better balance between science and education in order to better meet the needs of industry. These curricular changes are largely a result of revised ABET accreditation requirements. In response to these changes, new curriculum and analysis tools were developed for a power systems capstone design course. The project integrates market economics and socio-political considerations with transient stability analysis and transmission planning. A power systems analysis package and an economic analysis tool were developed for use with this project. Student evaluations of the course in which the project was implemented indicate that the curriculum successfully addresses a broad range of ABET accreditation criteria.**

***Index Terms*—Capstone Design, Engineering Education, Power System Operation, Simulation, Transient Analysis.**

I. INTRODUCTION

A. The effect of deregulation on education

ECONOMIC changes in the last decade and changes in the power systems industry have led to a paradigm shift in power system education. Although little has changed in the physical nature of power systems from the time before deregulation to the present, the types of skills sought by companies in the energy industry are changing. In summary of the results of a 1998 IEEE panel session on the state of power engineering education worldwide, Karady *et al.* remarked that, "the deregulated, competitive utility industry needs engineers with broader educational backgrounds. Basic knowledge in economics and management together with communication skills are required in addition to engineering knowledge [1]." As the energy industry becomes increasingly competitive, the financial aspects of power systems become increasingly important. Power engineers need a good understanding of the economic motivators that drive the industry in order to effectively contribute in the new market. Similarly, the production and transmission of electrical energy often has significant environmental and social consequences. The power system engineer should be aware of these consequences and how to mitigate them. Naturally, energy market participants are still seeking applicants with a strong understanding of AC power systems, but current job listings indicate that employers are also looking for applicants who understand financial markets, risk management, marketing, optimization, information technology, and broadband communications. Power systems educators and curriculum developers must effectively prepare students for the needs of the changing power industry.

B. Changes in engineering education

Engineering education is concurrently in a time of transition. Numerous reports have been written in the last two decades by organizations including the National Science Foundation [2], the National Research Council [3], and the American Society of Engineering Education [4], recommending changes in the way that engineering students are educated. Although their analysis of and recommendations for engineering education vary, one common theme is that engineering education needs to reflect a better balance between theoretical engineering science and practical application. In some ways this is a reaction to the movement in the early 1950s to increase the emphasis on science in engineering education [5]. The former changes came about because the majority of engineering professionals and academics did not participate in the development of new technologies that emerged during World War II because of the scientific background required for this type of innovation [6]. By the early 1980s these changes had been implemented so thoroughly that many in industry and some in academia felt that engineering schools had become too focused on pure science and that engineering graduates had become irrelevant to engineering industry.

One of the first reactions to this perceived imbalance between science and application was the inclusion of a "design component" in the ABET curricular requirements in the mid 1980s [7]. This requirement led most engineering schools to include a senior design or capstone course in their curriculum. The recent reports on engineering education are additionally recommending that engineering education should seek to attract a more diverse student population and that engineers

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The full text of the design project and associated tools presented in this paper are available at: http://www.ee.washington.edu/research/powerviz.

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should be trained to think more carefully about the economic and societal contexts of their work. One of the most visible consequences of these reports is the Accreditation Board for Engineering and Technology's (ABET) Engineering Criteria 2000 (EC 2000) [8]. Currently the standard for engineering accreditation in the United States and some schools elsewhere, EC 2000 is forcing engineering schools to redesign their programs with the aim of better preparing students to work in engineering professions.

EC 2000 requires that engineering programs include a "significant design experience" in their curricula. This requirement better defines the type of design curriculum that is to be provided for students. The new standard reads, "Students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier coursework and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political."[8] Also, EC 2000 requires that engineering graduates be able to demonstrate effective design skills upon graduation as well as being able to work in multidisciplinary teams, communicate effectively, and understand contemporary issues. The capstone design course is a good place in the engineering curriculum to address some of the non-technical aspects of an engineering discipline. Due to similar requirements, the new guidelines set out by ABET, when appropriately implemented, may help power systems programs improve their programs to better meet the needs of the changing power industry.

C. The challenge of capstone design in power systems

Most capstone projects are essentially the design and implementation of a new device to meet a given need. The project is almost always the design of a completely new product. This type of project is inappropriate for a power systems design course as the design of new electric utility power systems is very rarely done in industry. Design in power systems usually entails incorporating new components into an existing system, or perhaps merely the adjustment of the operation of an existing system. Design within the context of a power system is necessarily distinct from the design of a new electrical device. Existing power systems are generally the result of numerous sequential, possibly sub-optimal redesigns. Additionally, design prototyping is nearly impossible in power system design due to the cost and size of the components. In a power system capstone course it is virtually impossible to implement a design with circuit components as is done in many other EE capstone courses. Power systems designs are generally completed on paper before they are implemented in the system. Thus, simulation tools play a vital role in power systems design projects.

Some have resolved this difficulty by guiding students through a power system analysis software design project during the capstone course. For example, several years ago the final design project in the power systems capstone course at the University of Washington was to design a power flow analysis program. While this allows students to interact with power system science, it does not encourage students to learn the types of practical design skills that the majority of energy-industry employers are looking for. Other capstone instructors have had students design and build a power systems component such as a transformer or a relay. While this can introduce students to some practical design skills, it is not truly a power *systems* project because students are not required to interact with an existing power system. In order to be a power systems design course the project should challenge students to integrate new components into an existing network or to create a plan for changing the operation of an existing network to meet a given set of requirements.

Furthermore, the non-technical impacts of power systems are often more noticeable than in other EE disciplines. Deregulation is a fundamentally economic endeavor that contemporary power engineers must deal with extensively. Its effects (both positive and negative) are felt by a substantial portion of the population. This is currently noticeable in the Western US where California's deregulated market has been a major factor in allowing bulk electric prices to jump orders of magnitude higher than those before deregulation. Also, the construction of a new transmission line, substation, or generator can have a substantial impact on the land and the people living near the new construction and is often the subject of close and critical public scrutiny. If power system education programs are to prepare students for success in industry these non-technical issues should be dealt with at the undergraduate level. The capstone design course provides an excellent forum in which to address them.

II. THE TRANSIENT STABILITY DESIGN PROJECT

The goal in creating this design project was to create a pseudo-realistic scenario that encourages students to combine transient stability with economic, social, and political analysis. To meet this goal we created a scenario where the fictional "Western States System Operators Coalition" (WSSOC) has decided to conduct an extensive review of the western interconnect. The WSSOC would be roughly equivalent to the proposed RTO-West that will likely become the regional transmission operator for the Western power grid in the not too distant future. The WSSOC is looking into creating a plan for system expansion that will help to relieve congestion on the Northwest to California transmission corridor. They also plan to create a schedule for West Coast transmission system transfer limits and infrastructure growth considering transient stability limits and other technical and non-technical constraints. They plan to hold a meeting during which concerned parties will be allowed to present recommendations for how the WSSOC system should be upgraded and operated during the planning period.

In this scenario, several different fictional organizations (such as the "Northwest Generators Coalition" and the "Citizens for Reliable Electricity") are seeking engineering representation at this meeting. Student teams are asked to select an organization to represent before the WSSOC. The student groups must then prepare written and oral reports that explain their team's recommendations in detail. Students are expected to investigate several different design options including system expansion and operating limit changes and present the results of their analysis. The best design option was to be chosen from among those analyzed and defended in the students' reports.

The following is a summary of the steps required to complete this design project:

1. Find the stability transfer limit. This requires students to increase the generation in the Northwest and the load in California until the system is marginally stable based on a given worst-case contingency. Students were allowed to assume that this stability limit is constant for all combinations of load and generation. A binary search tool supervising a transient stability time domain simulation was developed to automate this process and given to the students.
2. Calculate the cost of congestion. The students were instructed to use hourly load data and an economic model (see section IIB) to estimate the congestion rent on the existing system given the current transfer limit.
3. Choose a new transfer limit. The transfer limit is defined as the sum of the calculated limit and a safety margin. In this part of the design process, students must consider the interests of their client and use ethical and engineering judgment. For example, the "Northwest Generator's Coalition" would probably advocate a lesser safety margin as generators in the Northwest could benefit from the increased ability to sell to the California market. Students were encouraged to consider the interests of their clients when determining an appropriate safety margin.
4. Calculate the cost of congestion. This was done using a spreadsheet developed for this purpose (see section II B).
5. Choose several expansion options. The students were given the options of either improving the system relays and circuit breakers (reducing the fault-clearing time) or building new transmission. The cost for each option is given in the project documentation.
6. Find the transfer limits and costs of congestion for each system expansion option with several different safety margins.
7. Choose the best option considering the stability of the system, the cost of expansion, the interests of their client, and other relevant factors.

This procedure was not explicitly given to the students so different teams naturally followed different paths through this design process, but the above steps were generally completed by the student teams.

A. The Reduced WSCC System

As discussed in the introduction, power systems design projects require a power system model. The base case model for this project was created to reflect heavy summer conditions on the Western System Coordinating Council (WSCC) system as represented by the NERC form 715 filing WSCC HS3SB [9]. The following criteria were used to develop the power system data:

1. The system should be appropriately sized so that it can be represented on a single page or computer screen and so that the analysis of the system is computationally and conceptually manageable. Conversely, the system should not be so small that the analysis is trivial. The system should convey some of the conceptual difficulty that comes with large power system analysis.
2. The system power flow should be convergent for the base case and for all line outage contingencies.
3. A relatively small increase in Northwest (NW) to California (CA) transfer should cause a transient stability problem.
4. The system should, at least marginally, reflect peak summer operation of the actual WSCC system.

These criteria were used to develop the 18-bus power system depicted in fig. 1.

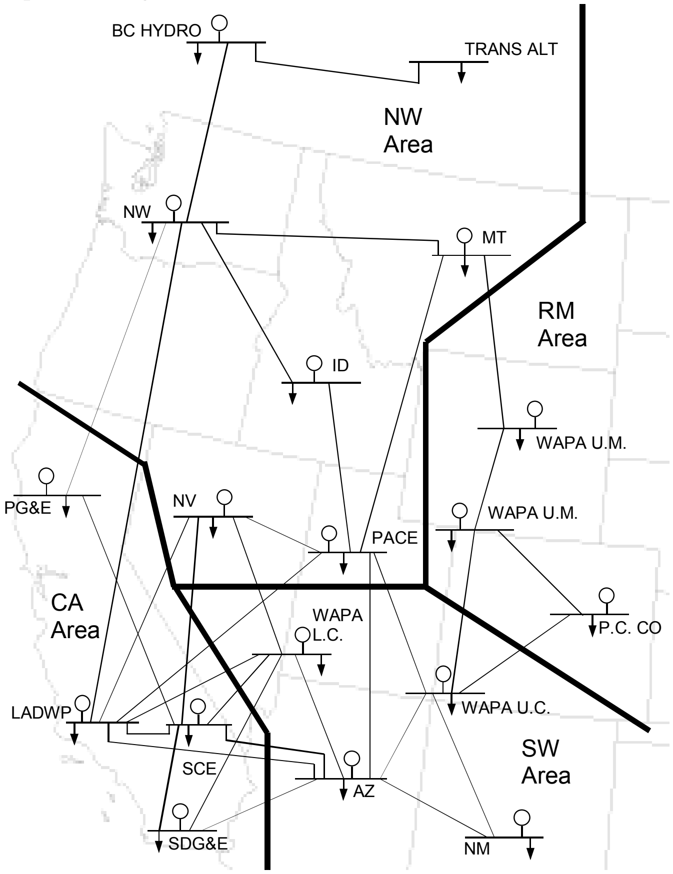


Fig. 1. One-line diagram of the 18-bus WSCC system used for this project.

We did not consider it of first importance to create a model that reflects the actual operation of the WSCC system with a high degree of accuracy. Thus, the generators are modeled as simple two axis machines with no AGC or exciter controls. The system is also somewhat abnormal in that most of its buses are generator buses. Despite these simplifications, the model acts generally as a power system should in that it becomes more stable when the NW-CA transfer is reduced and when additional transmission capacity is added.

B. Economic Model and Spreadsheet

In order to calculate the cost of congestion for the WSCC system, an economic model of the system was developed. The model was implemented in a spreadsheet which includes two main components: fabricated hourly load data for all 4 areas for each year between 1998 and 2008 and a means of calculating the constrained and unconstrained energy costs given the load data. The annual load data was estimated using 1998 monthly peak and mean load data for each area published by the WSCC [10]. A weekly load cycle and some randomness were added to this data to obtain hourly data for 1998. The resulting load curves are shown in fig. 2. Estimated growth factors published in the WSCC report are used in the spreadsheet to obtain demand data for subsequent years.

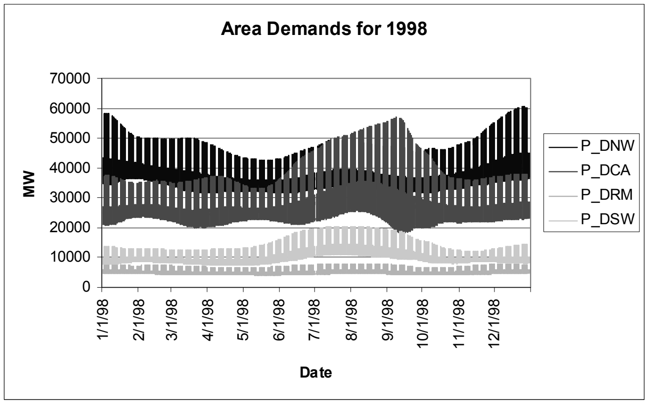


Fig. 2. Demand for the 4 WSCC Areas in 1998.

Several simplifying assumptions were made in order to simplify the congestion cost calculation. First, we assumed that all trades between the Northwest (NW) and California (CA) occur at a single price. This assumes that there is perfect competition and perfect price information. We also assume that transaction costs are negligible. With these assumptions we can lump the California power market and the Northwest power market into large market participants with non-decreasing incremental cost (or supply) curves. We further assume that the supply curves are linear. Observation of the actual California power market will quickly show that this assumption is inaccurate as price increases at a dramatically increasing rate when the demand approaches the available capacity. Nevertheless, this assumption simplifies the calculations substantially so the linear model was used. The two linear supply curves for the NW and CA areas can be described with:

$$IC_{NW} = a_{NW} + b_{NW} \cdot P_{G\_NW} \qquad (1)$$

$$IC_{CA} = a_{CA} + b_{CA} \cdot P_{G\_CA}$$

where P_{G_AB} is the total generation in area AB, a and b are scalars that define the incremental cost functions, and IC represents the actual incremental cost for the area. In the unconstrained case, the generation outputs can be determined by setting the incremental cost functions for both areas equal. Thus:

$$a_{NW} + b_{NW} \cdot P_{G\_NW} = a_{CA} + b_{CA} \cdot P_{G\_CA} \qquad (2)$$

Although this market model is simple, it is useful for the purposes of this project.

As a further simplification, we assumed that the generation in the Rocky Mountain and Southwest areas is directly proportional to the load at the current hour:

$$P_{G\_SW} = k_{SW} \cdot P_{D\_SW} \qquad (3)$$

$$P_{G\_RM} = k_{RM} \cdot P_{D\_RM}$$

where k_{SW} and k_{RM} are scalars, and P_{D_SW} and P_{D_RM} are the power demand in the two areas. Additionally, we assumed that the total system generation was equal to the total system load (zero transmission losses):

$$\sum P_G = \sum P_D \qquad (4)$$

From the above, the generation in the Northwest and California can be calculated, thus obtaining an unconstrained dispatch for the system. Using the price or incremental cost of electricity from (1) the unconstrained cost of energy was calculated for the entire Northwest/California system for an entire year.

Given the unconstrained solution one can calculate the constrained solution. For the sake of the congestion calculation, the transfer from the northwest (T_{NW}) was defined as the sum of the total MW transfer outside of the NW area; thus:

$$T_{NW} = P_{G\_NW} - P_{L\_NW} \,. \qquad (5)$$

If the dynamics of the system require that T_{NW} be limited at a certain value ($T_{NW}^{\max}$) the system is congested and (2) will not hold. P_{G_NW} will necessarily be limited to:

$$P_{G\_NW} = P_{L\_NW} + T_{NW}^{\max} \qquad (6)$$

The incremental costs will thus no longer determine the generation in the NW and CA areas resulting in a difference between the unconstrained cost of electricity and the constrained cost of electricity. The difference between the constrained and the unconstrained cost is a measure of the market inefficiency, and is necessarily positive (if there is congestion) or zero (if there is no congestion) [11].

The spreadsheet gives students the ability to view the cost of congestion for any year in the design period (1999-2008) given the calculated transient stability limit (TSL), and a safety margin (SM). This gives a value for the total transfer capacity (TTC) which was defined as the difference between the transient stability limit (TSL) and the chosen safety margin:

$$TTC = TSL - SM \qquad (3)$$

The total transmission capacity was then used in the cost of congestion calculation. Fig. 3 illustrates the relationship between transfer, price, capacity and demand.

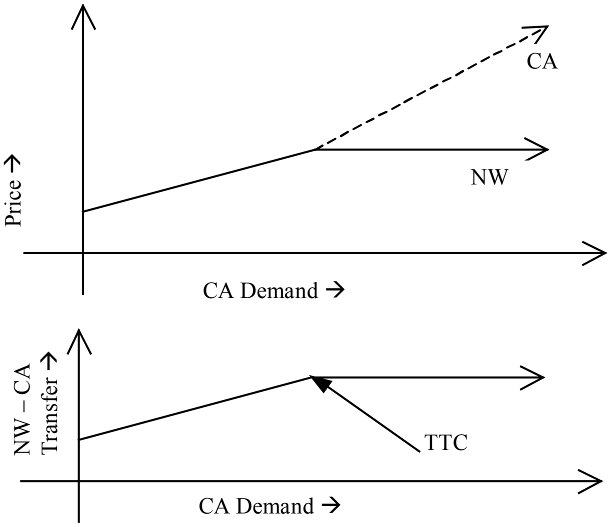


Fig. 3. Illustration of the relationship between demand, price and transfer. Until the transfer reaches the TTC point the prices in the NW and CA areas are equal. After this point the price in CA increases dramatically while the price in the NW remains constant.Power System Simulation Tool

III. THE POWER SYSTEMS ANALYSIS TOOL

In order to facilitate this design problem an analysis tool was developed which uses visualization to present calculated results. The program (called PowerViz) was designed to give students a fairly wide range of analysis options without the level of complexity required by a professional power systems analysis tool. The intention was to design a tool that allows students to expend minimal effort understanding the software and maximal effort solving power systems design problems. Currently the program includes three modes: power flow, n-1 contingency, and transient stability. The user interface (UI) design for this package was based on UI principles presented by Mahadev and Christie in [12]-[14], including the concept of task adaptive visualization [14]. The UI changes depending on the current user mode, allowing the user to see information that is most useful depending on the type of analysis that the user is working on.

The power flow mode can be used to calculate and view the power flow through the transmission lines of a system. The program uses a simple Newton-Raphson algorithm to calculate bus voltages and angles. The power flow data can be viewed visually on the screen (as shown in fig. 4) or numerically via the log file or a status bar in the lower left corner.

The n-1 contingency mode sequentially calculates the power flow for every possible line outage and similarly displays the results graphically. The UI used is based on the graphical methods presented in [13].

The transient stability mode allows the user to simulate a set of system events and view the time domain results. By choosing this analysis mode the user is prompted to enter the sequence of events to simulate. This dialog box is shown in fig. 6. In it the user specifies the event type, the time, and the location of each event. The dialog is programmed to only allow the user to enter the data needed for a given event type. The intention is to enable students who have minimal understanding of transient stability simulations use the program and understand the results. The user is allowed to choose between a variety of transient event types including:

1. Fault
2. Circuit Breaker Open / Reclose
3. Transmission Line Trip
4. Transmission Line Reclose
5. Generator Trip

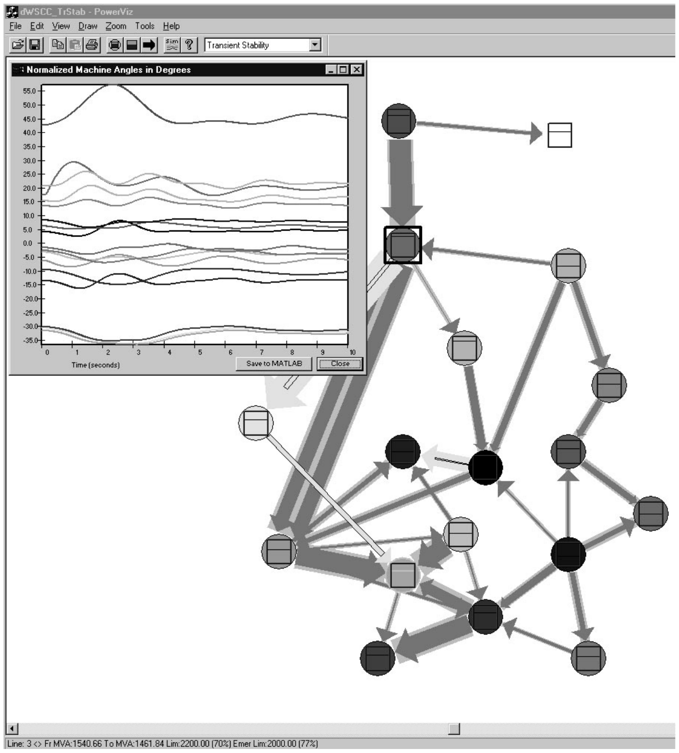
Other events simulating the effect of shunt breaking resistors on a generator bus and a fast relief valve for a generator are included in the event options.

When the user selects “Run Simulation” the program completes a time domain solution of the system algebraic and differential equations and displays the graphs selected by the user. Fig. 5 shows the transient stability view for the worst case contingency used to calculate the stability limit for this design project.

Power Flow

Bus:12<AZ> Type:Generator V:1.040 Angle:22 PGen:13867 QGen:2892 NORML UNLK NUM SCRL

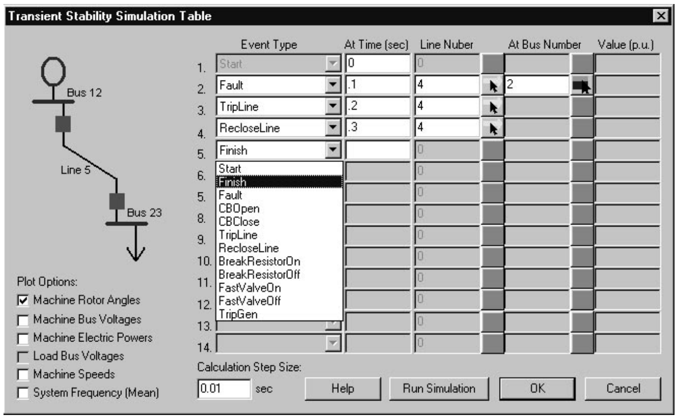
Fig. 4. PowerViz power flow mode visual interface. The 18 bus reduced WSCC system is shown here.



Transient Stability

Line: 3 <> Fr MVA:1540.66 To MVA:1461.84 Lim:2200.00 (70%) Emer Lim:2000.00 (77%)

Fig. 5. WSCC system and machine angles as shown after a transient stability simulation. The event simulated is a 0.8 second fault on bus 2, on the line between buses 2 and 4. The line is not reclosed after it is tripped.



	Event Type	At Time (sec)	Line Nuber	At Bus Number	Value (p.u.)
1.	Start	0	0		
2.	Fault	.1	4	2	
3.	TripLine	.2	4		
4.	RecloseLine	.3	4		
5.	Finish		0		
6.			0		
5.			0		
8.			0		
9.			0		
10.			0		
11.			0		
12.			0		
13.			0		
14.			0		

Plot Options:
☑ Machine Rotor Angles
☐ Machine Bus Voltages
☐ Machine Electric Powers
☐ Load Bus Voltages
☐ Machine Speeds
☐ System Frequency (Mean)

Calculation Step Size: 0.01 sec

Fig. 6. PowerViz transient stability event entry dialog box.

IV. RESULTS OF CLASSROOM IMPLEMENTATION

The design project presented in this paper was used during the spring of 2000 and 2001 in a course entitled “Computer-Aided Design In Power Systems” at the University of Washington (UW). This is the capstone course for the undergraduate power systems course sequence. The transient stability project was given to the students as the last of several small projects in the course. Students were given about 3 weeks to complete their analysis, design and reports. In general it seems that the project effectively met the intended goals of the course, although some improvement is possible. One possible improvement is to allow students to initially develop a portion of the economic analysis spreadsheet in order to better understand the economic analysis process. The full spreadsheet could be given to the students after this initial assignment to simplify the complete analysis.

The goal in designing the curriculum for this course was to engage students in projects that give then the opportunity to develop skills that are applicable to the current power systems industry as well as to meet EC 2000 requirements. As part of the UW engineering schools accreditation self-evaluation process students are asked at the conclusion of every engineering course to evaluate the course’s success in helping them develop the skills required of engineering graduates by ABET. Students were to evaluate how well the course prepared them to meet each of EC 2000 criteria 3(a) through 3(k) on a scale of one to seven. The results for this course (for the Spring 2000 offering) were higher than all other EE department capstone courses in all but two of the eleven categories. The mean rating for all capstone courses in all categories was 5.89 whereas the mean rating for this course was 6.71. These ratings indicate that the course prepared students especially well to demonstrate that they have: “(c) an ability to design a system, component, or process to meet desired needs,” “(g) an ability to communicate effectively,” and “(j) a knowledge of contemporary issues.” [7] Additionally it was one of only 2 courses in the entire EE department that students felt gave them “an understanding of professional and ethical responsibility.” [7] These data are an indication that the design curriculum developed for this course was successful. We set out to develop curriculum that gives students exposure to a broad range of issues. Students in the course felt like they were well prepared in such topics as communications, contemporary issues, and ethics.

V. CONCLUSIONS

In this paper a capstone design project has been presented which helps students to develop both technical and non-technical analysis and design skills. This project (along with other curriculum designed for this course) was designed to prepare students for employment in the current power systems industry, as well as to satisfy ABET EC 2000 accreditation criteria. Both a power system analysis software package and an economic analysis spreadsheet were developed to help students with the modeling and analysis required for this project. The project was given to students during the spring of both 2000 and 2001. Data collected from students about the course indicate that the course met ABET requirements significantly better than other courses offered at the University of Washington during the same quarter. This data also indicates that this course dealt with a broader range of topics than did other capstone design courses. We believe that the type of curricula used in this course, integrating technical and non-technical instruction and projects through well designed design projects, will lead to power systems graduates that are better prepared to participate in the changing power systems industry.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

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